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Effect of different energy loading forms on laser irradiation of metal target

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Abstract. As an important basis for the laser processing industry, the essence of laser irradiation process on metal materials is the interaction between laser and metal materials, involving multidisciplinary cross-coupling of optics, thermals and mechanics. Due to the great influence of the thermal effect on materials, the study of modern laser technology is generally believed that the energy of laser is mainly converted into heat. Based on the finite element software ANSYS, the thermal effects such as temperature field distribution and temperature rise process of metal materials under laser irradiation can be numerically simulated. In this paper, the laser irradiation of metal target plate is taken as the background, and the two laser energy loading forms of Heat Fluxes (HFLUX) and Heat Generation Rates (HGEN) are studied to find a more realistic numerical simulation method, which provides a reference for the numerical simulation of the thermal effect of laser irradiated metal materials.

1. Introduction

Laser irradiation of metal materials is an extremely complicated process. When a laser beam is irradiated onto the metal surface, the laser energy is converted into other forms as the irradiation time elapses, resulting in a series of physical and chemical changes on the surface and inside of the metal material. And the temperature also rises rapidly. The study of thermal effects in this process is of great significance for understanding the specific details of metal material temperature field distribution, temperature rise process and solid-liquid phase change under laser irradiation, and helps to further improve the laser irradiation theory.

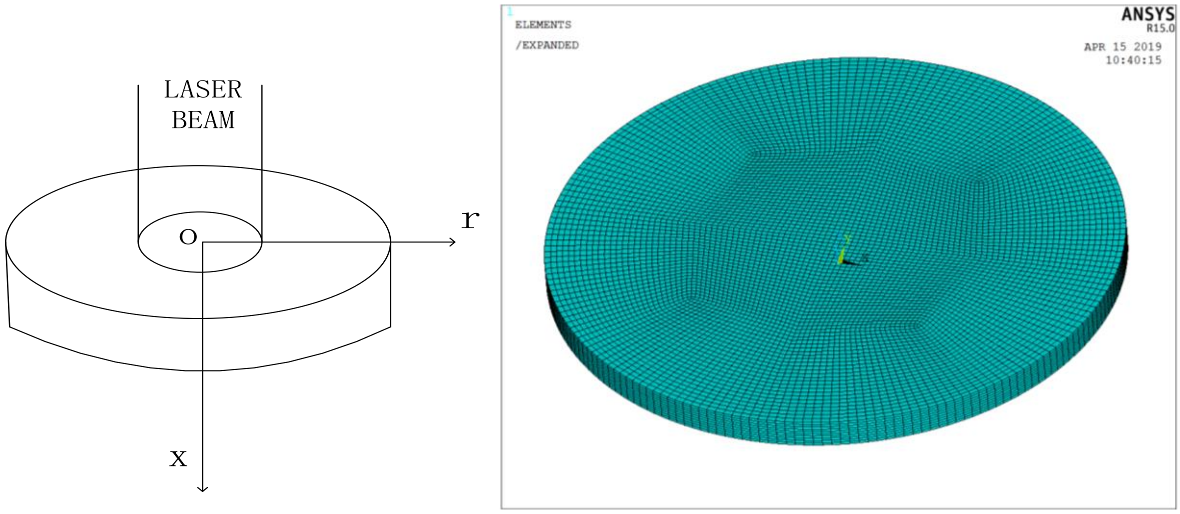
Due to the complexity of the laser irradiation process, it is difficult to obtain accurate results in theoretical research, and the emergence of finite element analysis software, to a great extent, has compensated for this deficiency. Based on the finite element analysis software, the corresponding numerical simulation can be carried out to obtain the instantaneous exact solution at any point or any time for the metal material during irradiation. And it can meet the requirements of geometric nonlinearity, material nonlinearity and contact nonlinearity of thermal analysis. The advantages are very obvious. Wang[1, 2] used the finite element software ANSYS to simulate the temperature field distribution of the alloy steel and the dynamic temperature rise of the front and back surfaces under the repeated frequency YAG laser irradiation, which was consistent with the experimental results. Based on the finite element technology, Valette [3] developed two two-dimensional temperature models to study the thermal effects of the interaction between femtosecond and nanosecond lasers and metallic materials. Chimier [4] established a heating and ablation model for metal targets, which was used to analyze the temperature field distribution and heat conduction process of metal targets under sub-picosecond laser pulse irradiation. The numerical simulation results agree well with the experimental results.

In the existing thermal analysis loading form of finite element analysis software ANSYS, there are two energy loading modes, the Heat Fluxes (HFLUX) and the Heat Generation Rates (HGEN), which are applicable to different situations. As the premise of accurate and reliable numerical simulation results, it is self-evident to determine the reasonable form of energy loading.

2. Model Establishment and Selection of Parameters

2.1. Model establishment

The theoretical calculation model and the finite element model are established respectively for the temperature field distribution of the metal target plate (two-dimensional axisymmetric model) under laser irradiation, as shown in Figure 1. The finite element model of the metal target plate is built by using a type of three-dimensional eight-node solid element (Solid70). The grid is divided by the mapped mesh, and the grid density should be as large as possible when the computer's working ability permits.



(a) Theoretical model (b) Finite element model

Figure 1. Model of laser irradiation metal target

2.2. Selection of parameters

The metal target plate is made of the common steel No. 45. The thermal performance parameters of the material are given in literature [5], as shown in the following Table 1 and Table 2. In order to simplify the calculation process, and to compare and analyze the effects of the two different energy loading forms on the temperature field better, the irradiation process can be controlled in a short time, so the temperature rise of the material is correspondingly small. According to the research results of the literature [6], it can be considered that the absorption rate of the incident laser remains constant at this time, and the absorption rate A is 0.37. Some other parameters for the metal target irradiation process are shown in Table 3.

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Table 1. Specific heat capacity of 45 steel at different temperatures

T/°C	100	200	400	600
Specific heat capacity c (J/kg °C)	468.9	481.5	523.4	573.6

Table 2. Thermal conductivity of 45 steel at different temperatures

T/°C	100	200	300	400	500	600
Thermal conductivity k (W/m·°C)	48.15	46.47	43.96	41.45	38.10	35.17

Table 3. Relevant parameters used in the calculation process

Density of 45 steel (kg/m^3)	Absorption rate	Target radius (m)	Target thickness (m)	Laser power density I_0(W/m^2)	Gaussian radius (m)
7810	0.37	0.05	0.005	1.0E7	0.005

3. Theoretical Derivation and Calculation

According to the thermal theory, the differential equation of transient heat conduction for the corresponding two-dimensional axisymmetric temperature field calculation model of the metal target plate under laser irradiation (Figure 1(b)) can be derived without considering the convective heat transfer and radiation heat transfer on the surface of the metal target. Also, the boundary conditions are available [7].

$$\rho c \frac{\partial T(x,r,t)}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T(x,r,t)}{\partial x}\right) + (1-R)\alpha I_0 \exp(-\alpha x) \tag{1}$$

The Front side of laser irradiation surface.

$$-k \frac{\partial T(x,r,t)}{\partial x}\Big|_{x=0} = \varepsilon I_0(r,t) \tag{2}$$

The back side of laser irradiation surface.

$$-k \frac{\partial T(x,r,t)}{\partial x}\Big|_{x=l} = 0 \tag{3}$$

Initial conditions.

$$T(x,r,0) = T_f \tag{4}$$

Where ρ, c, k define the density, specific heat capacity and thermal conductivity of the metal target material, respectively, T(x, r, t) defines the temperature field distribution of the metal target plate, and $I_0(r, t)$ defines the power density of laser when reaching the target surface, ε defines the energy absorption rate of the target surface to the laser, l defines the thickness of the metal target, and T_f defines the ambient temperature, $T_f=25°C$.

It is assumed that the intensity of the incident laser on the metal surface is Gaussian, that is, $I=I_0*\exp(-r^2/a^2)$, where a defines the spot Gaussian radius of the incident laser, and I_0 defines the power density

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of the center position of laser spot. According to the literature [8], the analytical solution of the above differential equation can be derived as follows.

$$T(x,r,t)=\frac{AI_0a}{k\sqrt{\pi}}\int_0^{\sqrt{\frac{4Dt}{a^2}}}\frac{\exp\left(\frac{-x^2}{a^2u^2}-\frac{r^2}{(1+u^2)a^2}\right)}{1+u^2}du+T_f \tag{5}$$

Taking the center point of the laser irradiation surface of the metal target as an example, x=0, r=0, the temperature rise function can be derived as shown in Formula (6).

$$T(0,0,t)=\frac{AI_0a}{k\sqrt{\pi}}\arctan\sqrt{\frac{4Dt}{a^2}}+T_f \tag{6}$$

With the specific parameter values substituted into the formula, the MATLAB numerical calculation software can be used to draw the curve corresponding to the above formula as a reference for the finite element simulation results. The temperature rise curve for the center position of spot in the target laser irradiation surface is shown in the following Figure 2.

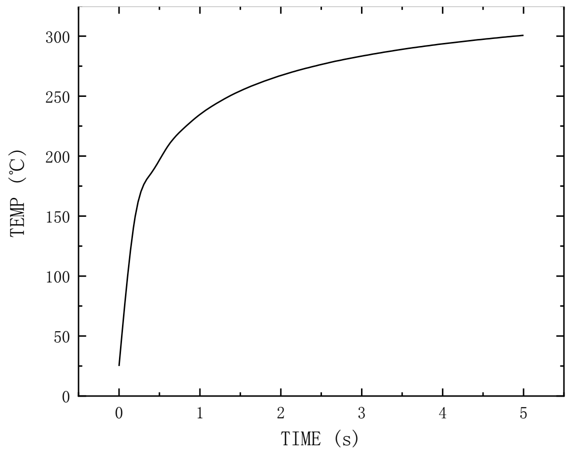

Figure 2. Analytical temperature rise curve

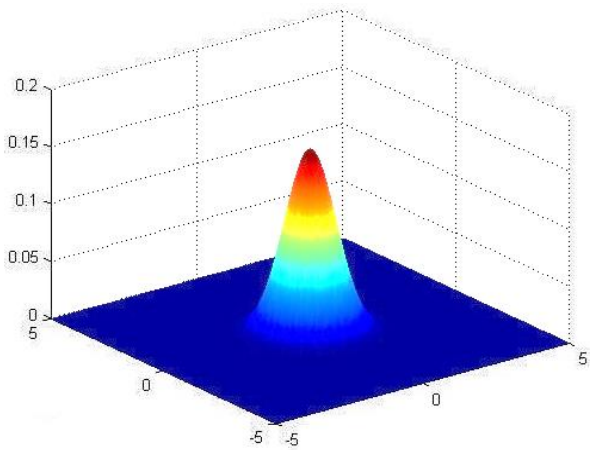

Figure 3. Model of Gaussian heat source

4. Finite Element Simulation

Heat Fluxes (HFLUX) is a kind of surface load, representing the heat flow rate per unit area, which can be applied to the case where the heat flow rate through the surface is known, and the positive value indicates that the heat flow input enters the model. HFLUX is only valid for body and shell elements. In general, it can be assumed that the laser beam is Gaussian distribution in space. And the energy form of laser can be regarded as a Gaussian heat source, as shown in Figure 3.Heat Generation Rates (HGEN) are applied as body loads and represent the heat generated by chemical reactions or current effects in the unit, which represents the heat flow rate per unit volume [9].

Since both the laser beam and the metal target have an axisymmetric property, a quarter model can be used for analysis. The boundary where no load is applied is treated as a complete adiabatic surface. The laser irradiation time was set to 5 seconds, and the calculation results were as follows.

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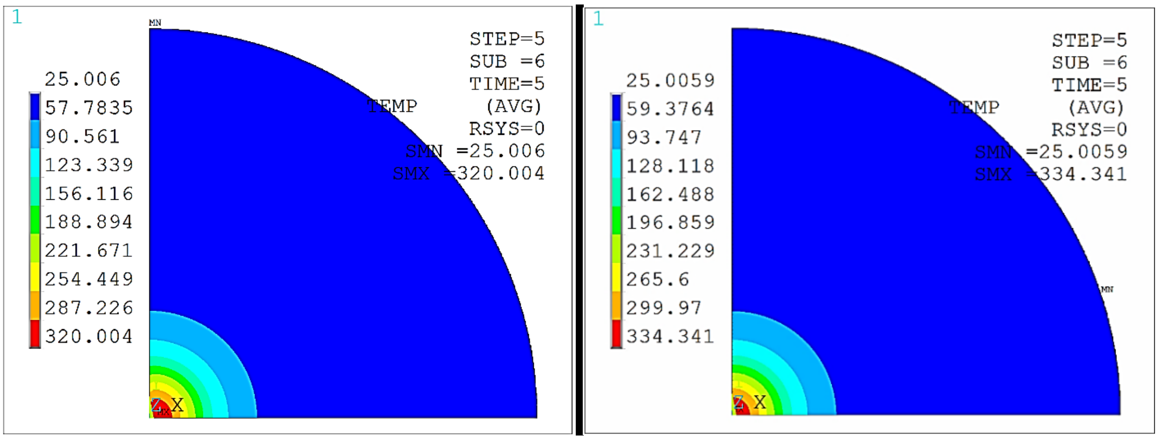
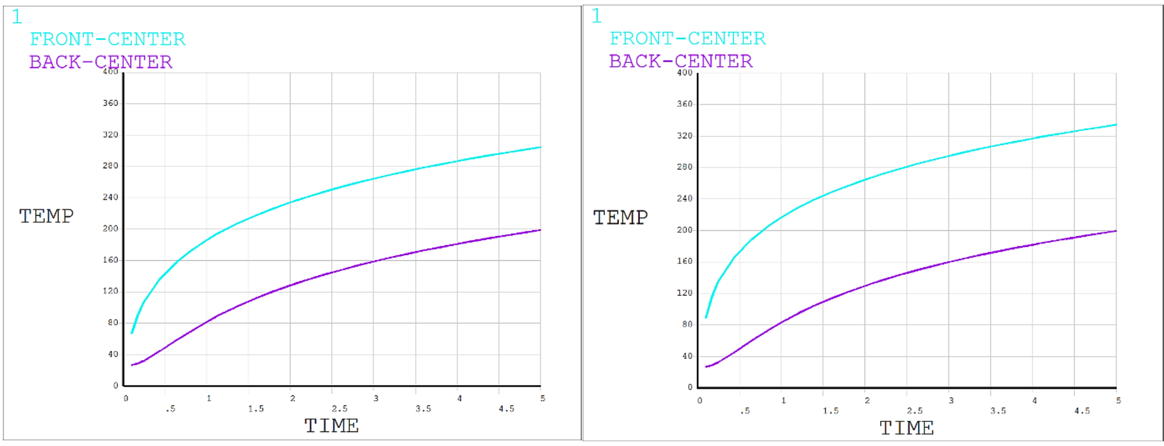


(a) HFLUX (b) HGEN

Figure 4. Temperature field cloud image of metal target at 5 seconds



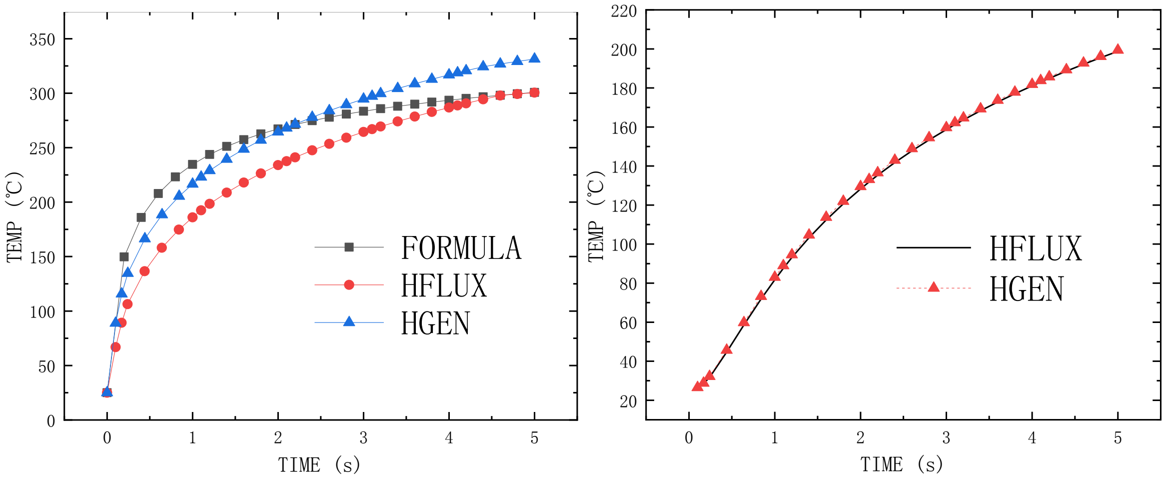
(a) HFLUX (b) HGEN

Figure 5. Temperature-time curve of the center point on the front and back side

It can be directly seen from Figure 4 and Figure 5 that the calculation results obtained by two different energy loading forms of HFLUX and HGEN are very similar, and the difference is not large.

5. Comparative Analysis of Calculation Results

The theoretical analytical solution is a kind of idealized result, which is based on the simplification and assumption of the solution conditions. And the simulation solution is the approximate solution with high precision of complex calculations performed by a computer, which is based on theoretical derivation. It is reasonable that there is a certain difference between the results. The results calculated by Formula (6) and the finite element software ANSYS are collated for further analysis, as shown in Figure 6.



(a) Center point of the front side (b) Center point of the reverse side

Figure 6. Temperature-time curves obtained by different methods

From Figure 6(a), the temperature rise curves obtained by two different energy loading forms of HFLUX and HGEN and the theoretically calculated curve of Formula 6 have a good fitting effect on the whole. The deviation between the analytical solution and the simulated solution fluctuates between 7% and 9%, but does not exceed 10%, which proves the high validity and reliability of the finite element simulation. At the beginning of the irradiation process, the theoretical solution curve grows faster than the finite element solution. The speed then slows down and the curve almost coincides with the HFLUX curve at the end. The reason may be that the theoretical calculation conditions are idealized and the energy enters the target directly, while the energy in the ANSYS simulation needs to pass through the element to the inside of the target, so the initial temperature rise is slow.

Comparing the two energy loading forms of finite element simulation, it can be seen that the trend of the temperature rise curve is substantially the same. But the temperature value of HGEN curve at the front center point is generally higher than the value of HFLUX curve, while the two curves at the center point of the reverse side almost completely coincide. The reason may be that HFLUX uses an energy areal density load and takes the energy deposition layer as a thin layer, while HGEN uses an energy bulk density load and the energy deposition layer is considered to have a certain thickness. Therefore, the element in the HGEN form absorbs energy more fully and the heat is transmitted more smoothly inside the target on the front side of the target. But the back of the target does not have such a problem.

6. Conclusion

Different energy loading forms are selected during the thermal analysis process, and the calculation results may have certain differences. Both forms of HFLUX and HGEN can be used to calculate simulations, but the HFLUX curve fits better. According to the literature [10], the absorption depth of the laser to the laser is about 10 nm, that is, the thermal effect of the laser on the target plate can be regarded as occurring only in an infinitely thin area of the surface. Therefore, considering the laser energy absorbed by the metal target as the surface heat flow is in line with the actual situation. In the finite element simulation of the laser irradiation, the HFLUX form should be used for energy loading.

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